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Please reference the final published version of this paper, available from: https://doi.org/10.1016/j.apenergy.2018.03.054

Prioritizing mitigation efforts considering co-benefits, equity and energy justice: Fossil fuel to renewable energy transition pathways

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KEYWORDS: Equity, Energy Justice, Health, Employment, Transition, Renewable Energy

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ABSTRACT

Transitioning from fossil fuels to renewable energy (RE) is one of the core strategies in developing sustainable future energy systems. But in planning such a transition, it is common to consider primarily cost and greenhouse gas reduction, as typified by cost-mitigation curves that have become widespread. Such assessments tend to leave important considerations of energy justice on the periphery. This paper puts forward an alternative assessment technique, incorporating various indicators of social equity in order to assess the priority of power plant replacement that would lead to the greatest improvement in benefits, while placing the burden of system changes away from the most vulnerable. An example of the application of this approach is presented for prioritization of the retirement and replacement (with RE) of Australia`s ageing fleet of coal-fired power plants. The assessment shows very different results from a standard cost-mitigation approach, with the retirement of the large brown coal power plants (including the recently retired Hazelwood power plant) and the replacement with wind power (where applicable) promoting the best overall outcomes on both cost and equity. Considering a selection of high priority indicators with many locally-specific data sets, the approach adds significant contextual relevance to prioritization, and is considered to offer useful findings for policy-makers.

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1. Introduction

Transitioning to a sustainable energy system is an important component of global sustainable development goals [1], and an important priority within these goals is the reduction of the use of fossil fuels and subsequent emissions of greenhouse gases (GHG), in order to reduce the possibility of excessive climate change [2]. Mitigation or abatement cost-curves are often used to compare the potential economic competitiveness and absolute mitigation potential of alternative measures [3]. However, as has been argued elsewhere [4, 5, 6], the co-benefits approach to evaluating mitigation technologies or efforts can often show alternative value associated with GHG reduction strategies that can potentially provide greater motivation for making such investments. Viewed from a different angle, it has been identified[7] that there is a lack of consideration of the holistic environmental, economic and particularly social impacts of energy policy. The equitable distribution of benefits, a key consideration of energy justice, and impacts of energy policy are addressed only after the policy is in place, if at all [8]. In this paper, we apply a multi-indicator evaluation, which quantitatively evaluates the distribution of social equity alongside traditional evaluation criteria, to examine a more-holistic prioritization of alternative mitigation choices in Australia, as an example.

Australia has one of the highest greenhouse gas emissions levels per capita among developed nations, due largely to its heavy reliance on black and brown coal within the electricity generation system which, in the case of the National Electricity Market (NEM) accounts for 74% of electricity output [9].

One strategy to ameliorate this dependence on coal-fired power generation and to reap the benefits of reduced greenhouse gas emissions and other pollutants is to retire coal-fired power plants, replacing them with renewable energy (RE) based alternatives. Due to the scale of Australia's largest (and most polluting) coal-fired power stations (13 generating complexes ranging from 1000MWe to 2840MWe are considered in this paper) this transition requires a massive deployment of RE in order to replace the lost generation within the NEM. This large scale (mega) wind or solar (PV) deployment which replaces coal-fired generation will have multiple impacts on both the energy system and society.

Building on the Energy Policy Sustainability Evaluation Framework (EPSEF) developed by the authors [7], an evaluation methodology is constructed to consider the employment, health, electricity price and greenhouse gas impacts of the transition from coal-fired to RE based generation.

The overall aim of this study is to determine a priority order for the retirement of the NEM's largest (>1000MWe) coal-fired power stations based on a range of Australian policy sustainability impacts, considering multiple policy priorities – particularly considering the energy justice ideal of the equitable distribution of benefits and impacts across society.

1.1. Fossil Fuel to Renewable Energy Transitions Evaluation and Energy Justice Considerations

A review of recent literature which evaluates energy transitions, specifically from fossil fuel to RE alternatives has identified that their focus is almost exclusively on the technological, environmental and economic outcomes, with limited concern for social impacts. For example, Wang et al found that research related to a transition to low-carbon electricity followed trends over time, focusing on technological responses[10]. These began with a recognition of the reliance on coal and nuclear baseload generation in the 1990's, generating an interest in the low-carbon alternatives of wind and CCS by the 2000's, followed by PV and natural gas in the 2010's. Energy efficiency was a constantly prominent research focus throughout, and the authors identify policy analysis and lifecycle assessment as future focuses. In terms of specific transitions from coal to alternative energy sources, Fakhry investigates the United States as a case study nation retiring coal in favor of renewable alternatives [11]. Her findings suggest that coal retirement offers an opportunity to transition to RE generation which will increase resilience while reducing emissions at a lower cost than the status quo.

Through a regulation based approach it is identified that energy efficiency, and integration of RE into a responsive grid will deliver environmental and economic benefits to households and businesses. In an analysis of the Chinese transition to a sustainable energy system, Sun et al assess 5 factors including the systemic factors of total capacity and excess generation, one economic factor of total annual costs, one environmental factor of CO_2 emissions, and one social factor, direct job creation[12)]. This small set of factors is used to assess sustainability, based on scenario energy mixes, and the authors identify the need for policy intervention to encourage greater RE deployment and cost as a barrier to a clean energy transition. In assessing the transition a more sustainable, lower emission generation supply in developing countries, Merzic et al consider three aspects of sustainability: techno-economic indicators, environmental indicators and social indicators [13)]. However, while economic and environmental indicators are robust, including a number of factors, social indicators only incorporate employment opportunities and electricity availability in qualitative terms, providing a ranking for each assessed scenario. It is common in the literature to find "social welfare" and "social impacts" being addressed by a single indicator – cost of electricity in the former case [14, 15)], and jobs in the latter [16)]. Some studies – particularly those addressing external costs of energy supply - have utilized health impacts, for example one study compared RE to energy efficiency[17)] . None of these studies focuses heavily on social impacts, even when their goal is to assess sustainability.

The concept of energy justice provides an avenue to bring social impacts of energy policy to the fore. In academic terms energy justice is a relatively recent phenomenon, studied as a defined concept since 2013 [18)]. The energy justice research agenda seeks to apply justice principles to broader energy issues and policy [19)], and is sometimes divided into three tenets, namely distributional, procedural and recognitional justice [20)]. Distributional justice is concerned with how the benefits and burdens of energy policy implementation are shared across society, i.e. who pays, who benefits, and why [21)]. Procedural justice on the other hand is concerned with an open and fair policy decision making process, such that all stakeholders have a voice, and the ability to participate in a meaningful way [20)]. Finally, justice as recognition seeks to identify groups who are misrepresented or discriminated against as a result of policy outcomes due to their views, social standing, cultural background or gender [19)].

Distributional justice has been somewhat of a focus in Germany in particular, due to the large uptake of renewables and the question of affordability of the feed-in-tarriff (FiT). One study examined the household expenditure as an indicator of social impact, finding greater impact on poorer households from increasing energy prices [22)]. Others have applied the Atkinson Index as a measure of societal inequality to study social welfare impacts [23)] and sustainability [24)] as a result of the German energy transition. But in these cases it is a national level consideration of energy justice that does not focus on specific locations or a ranking of technologies.

In terms of combining energy justice and energy transitions, in the short history of this research field, national level analyses have emerged. A pertinent example is that of the US, and the movement away from coal and oil based generation toward RE alternatives [25)]. This analysis considers the energy justice risks and opportunities for the implementation of five decarbonization strategies: divestment, carbon tax, cap and trade, deploying renewable energy and energy efficiency. The analysis brings energy justice concerns to the fore, identifying risks and opportunities for distributive, procedural and recognition justice across each decarbonization strategy. Disproportionate burden allocation in the energy sector is identified as an issue, in qualitative terms including 'clusters of ill health' and risks for politically and economically marginalized populations. Analysis of the UK, specifically with regard to nuclear power incentivization has also been undertaken, focusing on procedural justice, specifically transparency in allocating responsibilities.

Focusing on divestment, Healy and Barry identify the need for a rapid transition from fossil fuel based energy, agro-food and transport to low-carbon systems [26)]. Their focus is on the role of divestment in the political economy, in a "just" transition process. They pursue this analysis considering the democratizing of energy system transitions in order to deliver energy justice, considering fossil fuel divestment and associated labor issues. To accelerate the phase out of fossil fuels, the necessity for political action by civil society is highlighted, so as to reduce injustices in the transition, and to ensure that the transition is democratic. They identify the specific delegitimization of carbon as a possible approach, through the articulation of negative impacts and how these negatively affect not only the environment but also exploited communities at the point of extraction.

Jenkins et al identify the need to not only make energy policy participatory and more transparent, but a need to engage with energy justice concepts in order to overcome a moral vacuum in energy decision making [27)]. They advocate policy frameworks which prioritize transparency, such that the positive and negative energy justice implications can be identified and responsibility for these implications can be allocated.

1.2. Informing Energy Policy Using an Energy Justice Approach

Cognizant of the scholarship reviewed above, this study takes into consideration all three energy justice tenets, with distributional justice as the primary concern - measuring the distribution of environmental and economic outcomes of the replacement of coal fired power stations with RE. It measures these outcomes in terms of which sectors of society benefit, and which sectors bear the costs, expressed quantitatively as the "relative equity" and "policy burden" of explored options.

Further, the methodological approach identifies several justice as recognition issues. This is particularly evident in the health and employment impact analyses which drill down to a local government area level to assess the socio-economic status of those most affected by coal-fired power station pollutants and the change in employment in each income level as a result of the transition.

In terms of procedural justice, the overall aim of our approach is to inform energy policy decision making processes, to enable the shift from a traditional cost-curve approach toward an approach cognizant of social equity and energy justice issues. By employing the approach outlined in this study, the distributive and recognitional justice issues can be translated into energy policy priority settings to improve social equity and policy burden outcomes. Additionally, the incorporation of academic analysis into the policy making process, meets the role of energy justice as a decision making support tool for policy makers [18)].

The novelty of this research is the establishment of a fossil fuel replacement priority order incorporating energy justice issues. This type of plant-by-plant retirement schedule, considering a broad range of social costs and benefits is unique (to the authors` knowledge). In addition, due to the detail offered in terms of each specific social issue addressed, all three tenets of energy justice are considered, leading to applications in stakeholder engagement, energy policy decision making and implementation.

2. Methodology

The methodology employed to establish an equity-based coal-fired power station retirement priority for the Australian NEM is derived by modifying the EPSEF [7)] (see **Figure 1**) so that it can be used for a local level comparison (rather than its original target, at the national level). This localization is undertaken by estimating the impacts and benefits of replacement of coal power with RE within the same local government areas (LGA), after confirming that the land usage, employment capacity and pollutant spread can be estimated to impact within that area. The framework was initially augmented with additional equity factors derived from an energy policy and social equity hearing of policy practitioners and academics (respondents) with related expertise, undertaken from March to May of 2016. The hearing included an evaluation of respondents' understanding of social equity and also elicited the key factors of social equity (and their importance) considered critical by key policy influencers within Australia. Building on the responses gained, the framework was then adapted to include and assess these impacts alongside other policy decision-making factors in order to provide a methodology for holistic energy policy decision making - in this case specific to Australia. Recognizing that culture, user preferences and national trends influence energy transitions [28)], the factors identified in this study are not universal in nature and would need to be re-assessed for their applicability and perceived importance in other nations [29)].

The evaluation component of the framework incorporates six factors including health, employment, participation, subsidy allocation, electricity price impacts and greenhouse gas reductions, considering the magnitude and distribution of each of these impacts across socio-economic (income) levels. These six factors are applicable at the national level, but for the sake of the current study only four of the factors are considered relevant for application to a local, technology specific application, as outlined in **Figure 1**.

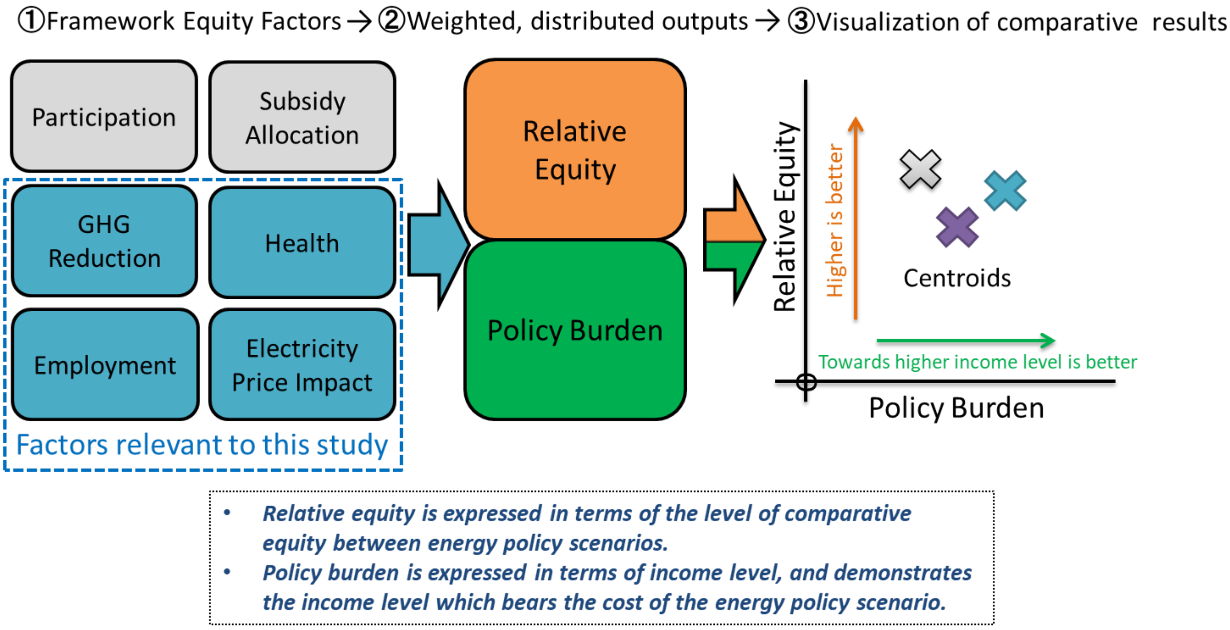

Figure 1. Equity Factors, Relative Equity and Policy Burden Outputs and Visualization

The four equity factors relevant to this study are shaded blue, in step 1 of **Figure 1**. Data required to calculate the value of these factors is accumulated from a variety of publicly available sources, and processed to the required format. Equity factors are then weighted relative to each other and distributed across socio-economic groups according to the factors outlined in **Table 1**. From this process, centroids for each case are derived to express the relative level of overall equity and the distribution of burden on societal income levels, as reflected at steps 2 and 3 of **Figure 1**.

The premise of the case study in this paper is that coal-fired power stations are replaced with sufficient wind or PV capacity to substitute for the equivalent pre-retirement grid electrical energy contribution. As the equity evaluation of a coal-RE transition in this paper does not cause the emergence of subsidization, or participation impacts (as a centralized energy system is maintained rather than individually-owned rooftop or distributed generation) these two of the six initial criteria were eliminated. The remaining four factors are calculated and weighted as outlined in **Table 1**.

Table 1. Comparative Equity Evaluation Factors

Equity Factor	Distribution Factors	Weighting Factors
1. GHG reduction benefit / impact	Assumed to be equally distributed.	Gt of GHG reduced in each location
2. Employment	Australian Case Study RE and fossil fuel job allocations and salaries.	Number of direct RE Jobs in the year of transition, less jobs lost in the fossil fuel industry.
3. Electricity price impact	Elec. price % change due to LCOE changes per income level.	Actual $ change per annual average electricity bill.
4. Health	$PM_{2.5\ \&\ 10}$ pollution distribution per capita in each income level.	TWh of fossil fuel generation reduced.

GHG reduction benefit or impact is assumed to affect all NEM consumers equally. This is considered reasonable for application in a developed country such as Australia, but may have more differential impacts in developing countries, or with a longer-term timeframe where adaptation to climate change becomes a significant concern. Employment impacts are assigned as losses of employment in the fossil fuel sector and gains in the RE sector, and are distributed by salary level to the different socio-economic strata of society. This is an initial estimate, based on the expectation that those qualified to take up roles "overnight" are in similar roles presently, and that these are represented by their current salaries. This assumption could be overturned with appropriate training programs implemented in order to move workers from lower to higher paying jobs. The electricity price impact is also applicable to all NEM consumers, distributed according to expenditure, and considers the change in price associated with installing RE. Health impacts are considered to be associated mainly with air-borne pollutant emissions, and here we utilize particulate matter ($PM_{2.5}$ and PM_{10}) as proxy measures.

Salient formulae for determining relative equity and policy burden are outlined below. Firstly, to determine the equity value (EV) for each income level:

$$EV_{(i,j)} = DV_{(i,j)} \times \left\{ \frac{WV_{(i,j)}}{MaxWV_{(i,j)}} \right\} \qquad \text{(eq. 1)}$$

where *EV* is the equity value, *DV* is the distribution value, *WV* is the weighting value, *i* (="very low", "low", "average", "high", "very high") is the income level, and *j* (=1,2,3,4) are the equity factors, as described in **Table 1**.

Using the four derived equity values for each income level, relative equity can be established thus:

$$\text{Relative Equity}_{(i)} = \frac{\sum_j EV_{(i,j)} \times w_{(i,j)}}{\sum_j w_{(i,j)}} \qquad \text{(eq. 2)}$$

where w_j is the weighting assigned to each equity factor (each factor is weighted equally in this research, based on energy policy expert feedback).

Relative equity values can then be plotted for each income level, leading to the derivation of a policy burden and relative equity (x and y coordinates respectively) centroid using geometric decomposition of the resultant polygon in an area-weighted approach, thus:

$$x = \frac{\Sigma C_{k_x} A_k}{\Sigma A_k},\ y = \frac{\Sigma C_{k_y} A_k}{\Sigma A_k} \qquad \text{(eq. 3)}$$

where *C* is the centroid and *A* is the area of individual income level rectangles *k*, within the plotted polygon.

Policy burden is calculated by subtracting the derived *x* values from an 'ideal' maximum value of 100, to determine whether the burden of retiring a specific power station is borne by higher (nominally, a policy burden score >50) or lower (a policy burden score <50) than median income households. The y-value represent the relative equity score. Higher scores are considered better, and outcomes are easily compared on a single graph. In addition to the four social impact factors outlined in **Table 1**, the cost of deployment of each feasible RE replacement technology will also be explored as a decision-making variable.

Based on the inputs described above, the methodology is designed to output four decision making values for each of the considered power stations: Health impacts (ΔPM), environmental impacts (ΔGHG), economic impacts (ΔCost), and overall social equity impacts (a combination of distributed economic and environmental costs and benefits).

These outputs can be combined to form a final "priority score", or considered individually according to policy priorities in order to determine objectively which of the 13 largest coal-fired generation complexes in the NEM (detailed below in **Table 2**) should be retired first.

Table 2. Largest Coal-Fired Generation Complex Details for the NEM

Complex Name	**Location**	**Capacity (MWe)**	**Capacity Factor#**
Bayswater	New South Wales	2640	73.2%
Callide B & C	Queensland	1600	60.9%
Eraring	New South Wales	2840	51.3%
Gladstone	Queensland	1680	45.8%
Hazelwood	Victoria	1600	80.6%
Liddell	New South Wales	2000	44.9%
Loy Yang A & B	Victoria	3165	89.9%
Mount Piper	New South Wales	1400	72.0%
Stanwell	Queensland	1460	65.5%
Tarong & Tarong North	Queensland	1843	56.6%
Vales Point B	New South Wales	1320	60.6%
Wallerawang-C	New South Wales	1000	52.0%
Yallourn West	Victoria	1480	80.8%

 # Capacity factor averaged over operating years between 2011/12 and 2015/16 financial years [30]

The methodology for the calculation of key input factors for energy policy decision making to both inform and augment social equity calculations is described below.

2.1. Cost

The two RE options being considered in this study to replace the coal-fired power stations are PV and wind. The deployment of mega solar is practicable at different levels of efficiency in all cases, however deployment of effective wind power is only possible for the Tarong & Tarong North, Mount Piper and Wallerawang-C complexes (based on local average wind speeds [31]).

The cost of mega solar projects is calculated on a per MW basis, including land, connection to the grid and panel deployment costs, reported by the AGL (Australian Gas Light company) Nyngan [32] (102MWp) and Broken Hill [33] (53MWp) large-scale solar PV projects (using the average of these plants). These project case studies also provide the area required per MW deployed and ongoing employment numbers. Similarly, the AGL-operated Hallett [34], Oaklands Hill [35] and Macarthur [35] wind farms provide an evidence base for wind power costs, employment numbers and the area required for wind farm deployment. For mega solar the cost per MW deployed is $2.84 million and for wind farms, $2.65 million[a].

2.2. GHG Reduction

The reduction in GHG due to the retirement of each coal-fired generation complex is calculated according to the type of fuel, annual generation amount[9] and GHG intensity factors for coal-fired and RE- based generation within the NEM [36),37),38)]. The GHG intensity factors are as follows:

1. Black Coal: 0.87 t $CO_{2\text{-}e}$/MWh
2. Brown Coal: 1.25 t $CO_{2\text{-}e}$/MWh
3. Solar PV [b]: 0.036 t $CO_{2\text{-}e}$/MWh
4. Wind [c]: 0.0093 t $CO_{2\text{-}e}$/MWh

Generation totals are calculated according to the NEM average capacity factors for each coal generation complex, detailed in Table 2. Average solar PV panel generation figures and capacity factors are based on their deployment location within the NEM, as follows [39)] :

1. Queensland: 1533 MWh / year / MWp deployed (CF=17.5%)
2. New South Wales: 1424 MWh / year / MWp deployed (CF=16.3%)
3. Victoria: 1314 MWh / year / MWp deployed (CF=15%)

For wind power, capacity factor is assumed to be constant, at the NEM-wide average of 29.7% (2600 MWh / year / MWp deployed [9)]), as the three sites considered in this research all have similar wind speeds.

2.3. Employment

Employment impacts (i.e. jobs lost due to retirement of generation facilities) are calculated for coal-fired power stations based on a case study using selected power station and generator annual reports and databases [40, 41, 42)] these are assumed to be the same for all complexes assessed, approximately 23.2 full-time, direct jobs per TWh generated per annum. The distribution of full time jobs and their approximate remuneration is summarized in Appendix A [43)].

With regard to solar PV long term jobs gained, the two mega-solar case studies (described in the cost sub-section) identified that approximately 46.3 full time employees were required per GW of solar panels deployed. For wind farms, the three abovementioned case studies suggest that long term maintenance job numbers are approximately 87 full time employees per GW of wind turbines deployed. The maintenance job salaries for solar PV and wind are summarized in Appendix B, with job types derived from the authors' Australian RE policy case study [44)] and AGL case study data, applying average RE industry wages [45)] across job types.

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[a] All figures in this study use Australian Dollars.

[b] Average life-cycle GHG emissions of the three dominant panel technology types; Mono-Silicon, Poly-Silicon and Cadmium-Telluride.

[c] Onshore Wind Turbines

2.4. Electricity Price Impacts

Electricity price impacts are determined through a consideration of the change in the overall levelized cost of electricity (LCOE) in the NEM due to the change in amount and type of generation. The plant-specific LCOE figures are adjusted from a general LCOE given for each type of generation [46) based on historical capacity factors for each coal fired power station over the last financial 5 years (2011/12-2015/16 [30)]), wind speed and solar irradiation, which were used to adjust the projected LCOE values for the year 2020 [46)] as shown in **Table 3.** The LCOE was used as the most readily available data, although in other cases it would be preferable to utilize facility-specific financial data on operating costs and specific sale prices of electricity to the grid.

Table 3. 2020 LCOE for Electricity Sources in the NEM

Fuel Source	LCOE$/MWh
Black Coal	$84.49~$137.72
Brown Coal	$67.45~$75.24
Wind	$73.97
Solar PV	$140.02~$163.36

2.5. Health Impacts

In order to determine the distribution of health impacts, particulate matter ($PM_{2.5}$ and PM_{10}) emissions, associated with health risks (including respiratory and cardiovascular morbidity [47)]) are used as a proxy indicator due to the relatively localized impacts of these emissions. The existing coal-fired power station locations, and the number and socio-economic status of households within the surrounding local government area of the power station (including all LGA'S within a 20km radius) are used to identify the impacted population. The assumption is made than any reduction in particulate emissions will engender a proportional improvement in health outcomes – linearity is implicitly assumed for the sake of simplicity, although it is acknowledged that this may not be the true relationship [48)]. The Australia Government provided National Pollutant Inventory (NPI) [49)] is utilized to estimate $PM_{2.5}$ and PM_{10} emissions in each case, whilst Australian Socio-economic Indexes for Areas (SEIFA) [50)] are used to identify the socioeconomic status of impacted households in the affected LGAs surrounding the generation facilities explored. The allocation of impacts across socio-economic groups is undertaken using the income and employment figures of the specific LGAs impacted by power plants.

The LGA, population and socio-economic decile (on a scale of 1-10, low to high) of each of the investigated coal-fired generation complexes is summarized in Appendix C. SEIFA deciles are reconciled with Australian average income levels [51)]in Appendix D. Higher heating values (HHV) for coal combustion [49)], used for PM emissions calculations are detailed in Appendix E.

LGA income profiles of locales hosting power generation complexes are shown in **Figure 2**. When more than one LGA is impacted, data is summed and averaged.

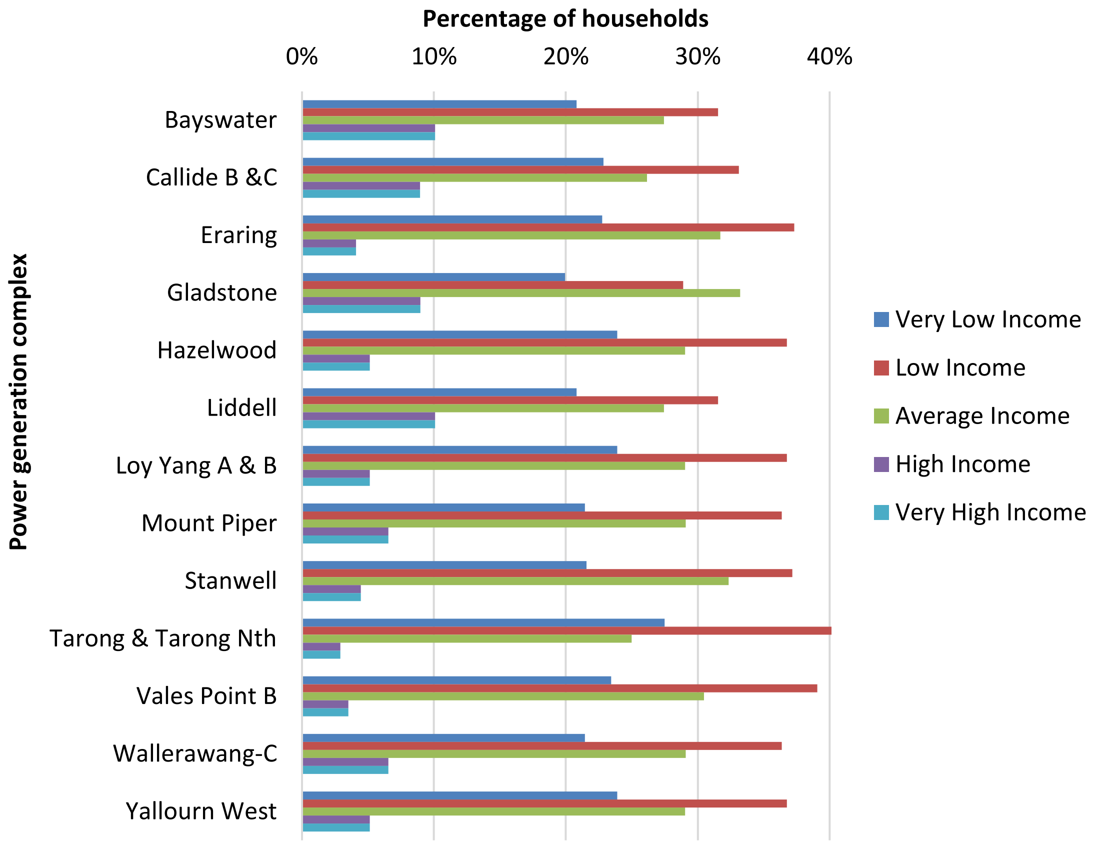

Figure 2. Distribution of incomes in the LGAs associated with power generation complexes

$PM_{2.5}$ and PM_{10} emission totals for each power station are calculated using the average annual emissions for the period 2012-2016 [52)].

2.6. Limitations

The assessment methodology outlined above has several limitations. First, the number and range of factors considered, although informed by expert input are by no means exhaustive, and could be augmented through key stakeholder engagement, or a broader survey of households across the investigated jurisdiction. Additionally, each of the factors assessed relies on a 'proxy' measure to calculate the distribution and weighting of cost and burdens imparted on society. This limitation may be overcome through a more specific investigation of each factor, and the introduction of a more exhaustive set of sub factors, based on evidence in the literature or through stakeholder engagement.

With regard to the data used to inform the selected factors, while care is taken to utilize accurate and relevant data, a number of data points represent regional or national averages, particularly with regard to employment outcomes, capacity factors and LCOE. It is anticipated that as additional case studies become available as a result of the increased deployment of RE in Australia, that these ranges can be narrowed, and results improved.

Finally, the results presented offer a snapshot for the year 2020 and assume that transition from fossil fuel to RE based generation would be smooth, and as discussed below, ignores the need for technologies (including storage) to deal with intermittent generation sources.

3. Results and Discussion

This section discusses and compares the traditional and newly proposed evaluation approach outcomes for the replacement of coal fired power stations with RE alternatives. This assessment begins with the traditional cost curve approach, followed by an evaluation using the EPSEF, and finally a combined approach to provide detailed comparative analysis for policy decision makers.

Firstly, the raw results for cost of replacement from coal to PV (and wind where practicable), resultant GHG reductions, and change in the number of jobs are summarized along with land requirements, LCOE impact across the NEM and health impacts in terms of PM reduced by the transition to RE for solar and wind based generation in **Table 4**.

Table 4. Summary of Coal to RE Transition Impacts

Complex Name	Transition Cost ($B AUD)		GHG reduction (kt/yr)		Employment Increase (jobs)		Land Required (km^2)		LCOE Impact ($/MWh)		Health Impact (PM t/yr)	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Bayswater	33.8		14,119		158		302		2.4		1123	
Callide B &C	15.8		7,118		60		142		1.2		1660	
Eraring	25.5		10,644		119		228		1.8		763	
Gladstone	12.5		5,622		47		112		1.0		300	
Hazelwood	24.4		13,714		136		219		1.7		4872	
Liddell	15.7		6,560		73		141		1.1		759	
Loy Yang A & B	53.7		30,259		301		483		3.8		6725	
Mount Piper	17.6	9.0	7,365	7,600	82	91	158	657	1.3	-0.74	391	
Stanwell	15.5		6,987		58		139		1.2		1282	
Tarong & Tarong Nth	17.0	9.3	7,621	7,865	64	93	152	680	1.3	-0.76	3454	
Vales Point B	14.0		5,844		65		126		1.0		120	
Wallerawang-C	9.1	4.6	3,799	3,921	43	47	82	339	0.7	-0.39	1808	
Yallourn West	22.6		12,717		127		203		1.6		4071	

In a typical consideration of whether to undertake an individual plant replacement, any of these factors could be individually seen as important. For example, considering the impact on retail electricity prices, in most cases, wind power alternatives reduce prices, whereas solar power causes an increase. However, the magnitude of such price increases is affected by the scale and efficiency of the plant being replaced, as well as location, but does not include either factor specifically in a single indicator evaluation.

Considering the type of employment affected by the retirement of coal-fired plants and their replacement with PV or wind, **Table 5** shows the distribution of the job changes for each generation complex. It is apparent that there is a shift away from higher income jobs towards lower income jobs in the case of PV, while wind produces better outcomes across the low-high income range. This type of distribution of jobs impacts on the equity assessment of the scenarios, and we can also consider that it clearly impacts differently according to the scale of capacity being retired and the socio-economic mix of the LGA in which that generation complex is situated.

Table 5. Net change in employment associated with coal plant retirement

Complex	Technology	Net change in employment (number of fulltime jobs)					
		Total	Very Low Income	Low Income	Average Income	High Income	Very High Income
Bayswater	PV	158	60	105	-2	-	-5
Callide B &C	PV	60	24	40	-1	-	-2
Eraring	PV	119	46	79	-2	-	-3
Gladstone	PV	47	18	31	-1	-	-2
Hazelwood	PV	137	53	91	-3	-	-4
Liddell	PV	74	29	49	-1	-	-2
Loy Yang A & B	PV	301	115	200	-5	-	-9
Mount Piper	PV	82	32	55	-1	-	-2
Mount Piper	Wind	91	-	25	35	34	-2
Stanwell	PV	60	23	40	-1	-	-2
Tarong & Tarong Nth	PV	65	25	43	-1	-	-2
Tarong & Tarong Nth	Wind	94	-	26	36	35	-3
Vales Point B	PV	66	26	44	-1	-	-2
Wallerawang-C	PV	43	17	28	-1	-	-2
Wallerawang-C	Wind	47	18	32	-1	-	-2
Yallourn West	PV	127	-	35	49	46	-4

By way of further illustration, **Figure 3** shows the change in jobs in each income level as a percentage of the pre-retirement jobs at that income level in the affected LGAs. It is apparent that some LGAs will benefit significantly more in certain income levels than others. Factors like this can play an important part in determining the balance of benefits and impacts on relative equity and the policy burden associated with mitigation strategies.

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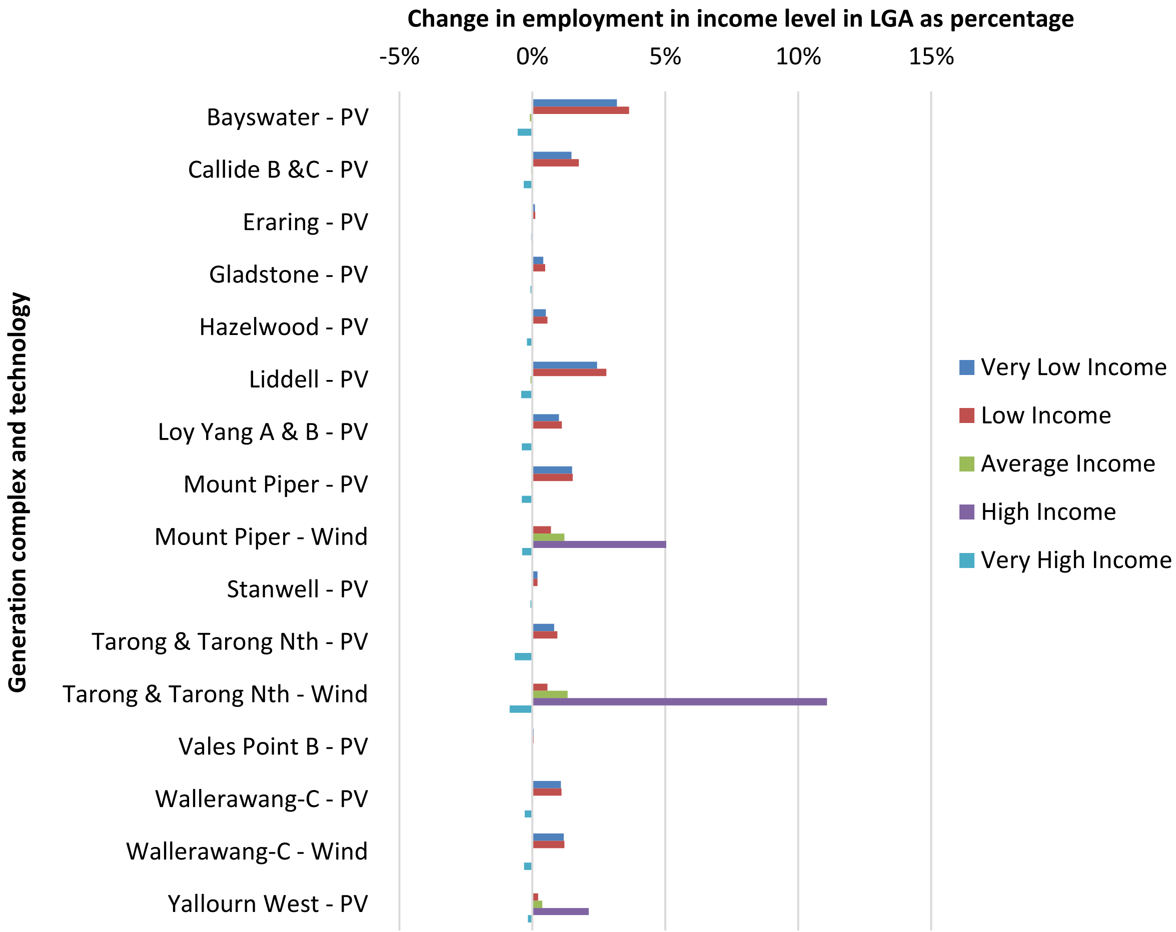

Figure 3. Change in jobs at each income level, as a percentage of total income level employment in affected LGAs

A typical approach to assessing more than a single factor, and to give some level of objective comparability to the alternative assessment options would be to examine the cost-effectiveness of the mitigation strategy. Considering a version of the typical mitigation cost-curve (**Figure 4**), it is apparent that wind power is the most cost-effective wherever it is applicable (identified as ① in the figure below). The second most cost-effective is PV replacement of brown coal (identified as ②) which is the highest emitting source, while black coal replacement by PV is most effective in Queensland (identified as ③, where there is a better solar insolation rate) than in the southern states (identified as ④ in the figure).

Such typical approaches however, do not include the distribution of benefits or impacts across socio-economic levels, which is addressed here by the application of the EPSEF, described earlier.

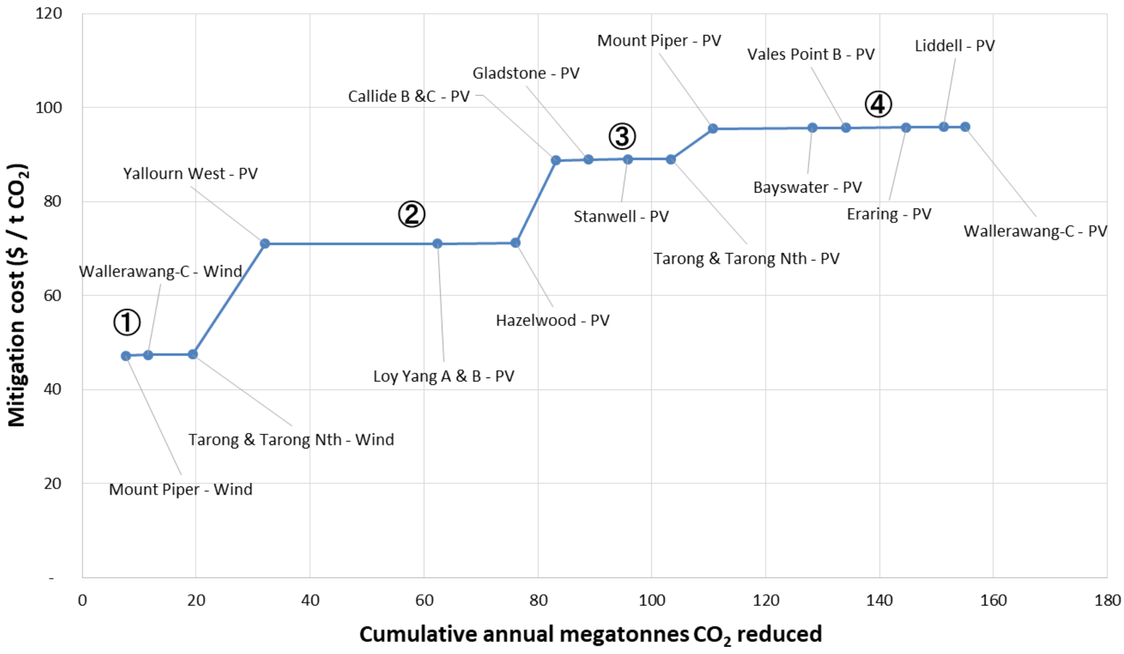

Figure 4. Typical mitigation cost-curve for coal-fired power plants in Australia considering a RE plant lifetime of 25 years

To enable a comparative equity evaluation between coal-fired generation complex replacement options, the results of applying the EPSEF to the four key equity factors of health, electricity price impacts, greenhouse gas reduction and employment are assessed. Comparative equity is expressed for each generation complex in terms of the level of relative equity, and a measure of the distribution of policy burden across income levels. As stated in the methodology, a higher score is preferable in both cases.

Table 6 outlines the relative equity and societal burden outcome and comparative rank for replacement of each generation complex with RE options. In both cases, it is apparent that the equity assessment provides a different result from any of the individual indicators on its own, or to the standard cost-curve approach.

Table 6. Generation Complex Relative Equity and Societal Burden Scores and Ranking

Generation Complex	Relative Equity Score	Rank	Policy Burden Score	Rank
Bayswater - PV	16.4	5	53.1	12
Callide B & C - PV	10.4	10	53.6	10
Eraring - PV	12.1	8	53.7	8
Gladstone - PV	5.3	16	49.7	16
Hazelwood - PV	27.0	2	57.5	2
Liddell - PV	8.3	13	53.6	9
Loy Yang A & B - PV	**47.5**	**1**	56.2	5
Mount Piper - PV	7.9	14	52.8	13
Mount Piper - Wind	14.6	7	50.8	15
Stanwell - PV	9.2	11	53.5	11
Tarong & Tarong North - PV	15.3	6	**58.1**	**1**
Tarong & Tarong North - Wind	22.5	4	55.2	6
Vales Point B - PV	5.8	15	52.6	14
Wallerawang-C - PV	8.6	12	56.5	4
Wallerawang-C - Wind	11.9	9	53.9	7
Yallourn West - PV	23.6	3	56.9	3

In the case of relative equity, for each generation complex, scale plays a large part in the overall score, as a comparatively large amount of both greenhouse gases and PM are reduced as a result of the transition to RE alternatives. Additionally, the larger and more efficient the complex, the more RE jobs are created. It should be noted that the relative equity scores are not set an upper limit or normalized in this case, but should be largely used as an inter-plant comparator.

With regard to policy burden distribution, scale does not have as significant an impact as was found for relative equity. In all cases except for Gladstone, policy burden scores are greater than 50, suggesting that a transition away from coal to RE is beneficial in almost all cases. This would imply that a transition from coal to RE at Gladstone would place a higher burden on lower income groups, while all other options would place the burden largely above the median income. The difference between policy burden scores for each complex is very small (within a 9-point range) when compared to relative equity scores.

In order to make a combined, comparative assessment, we plot the two factors of relative equity and policy burden against each other as shown in **Figure 5**. In this figure, the ideal option would be located in the top-right corner of the graph. However, it is apparent that no ideal solution exists, and it is therefore important to specify a preference for either high relative equity or a good outcome in terms of policy burden. As the policy burden scores are not widely distributed, it may be appropriate to prioritize relative equity. In this case, the Loy Yang A & B power complex would provide the greatest overall contribution to equity despite the policy burden score being slightly lower than some of the other options.

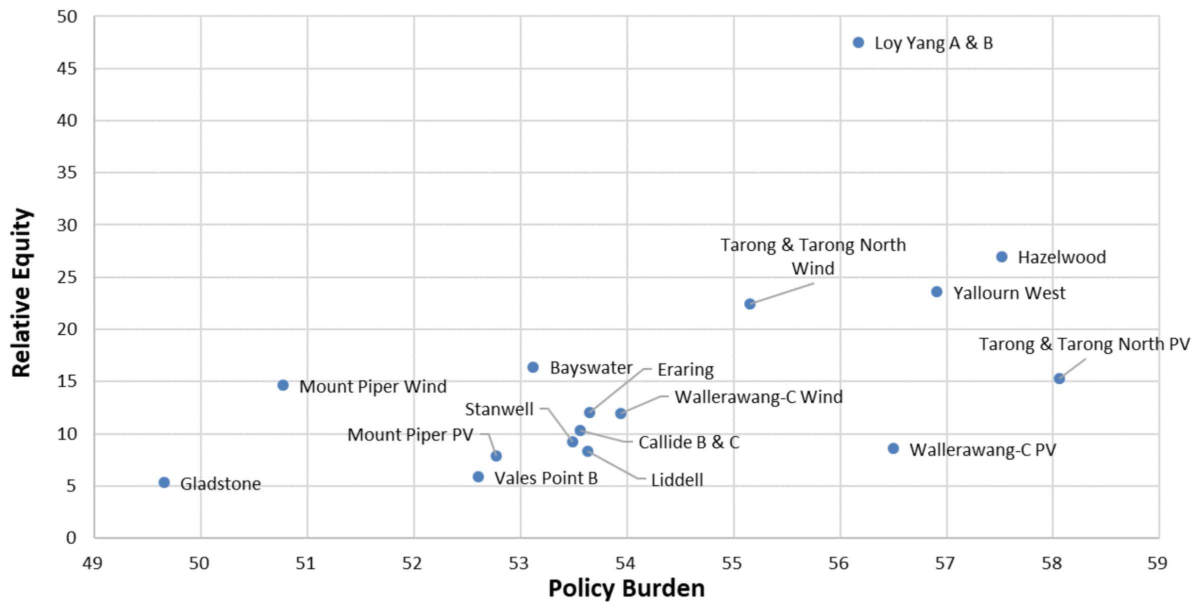

Figure 5. Relative equity versus policy burden results of replacing fossil fuel generation complexes with RE generation alternatives.

This approach can also be combined with the standard mitigation cost-curve approach as shown in **Figure 6**, in which we can clearly see the most equitable solutions are often, but not always, large emission-reducing options. Comparing both mitigation curves (**Figure 4** and **Figure 6**), it might be argued that the retirement of the Tarong & Tarong North complex of power plants, and their replacement with wind power, is the most effective solution on both counts, as it is cost-effective compared to replacing other complexes, while still improving equity significantly.

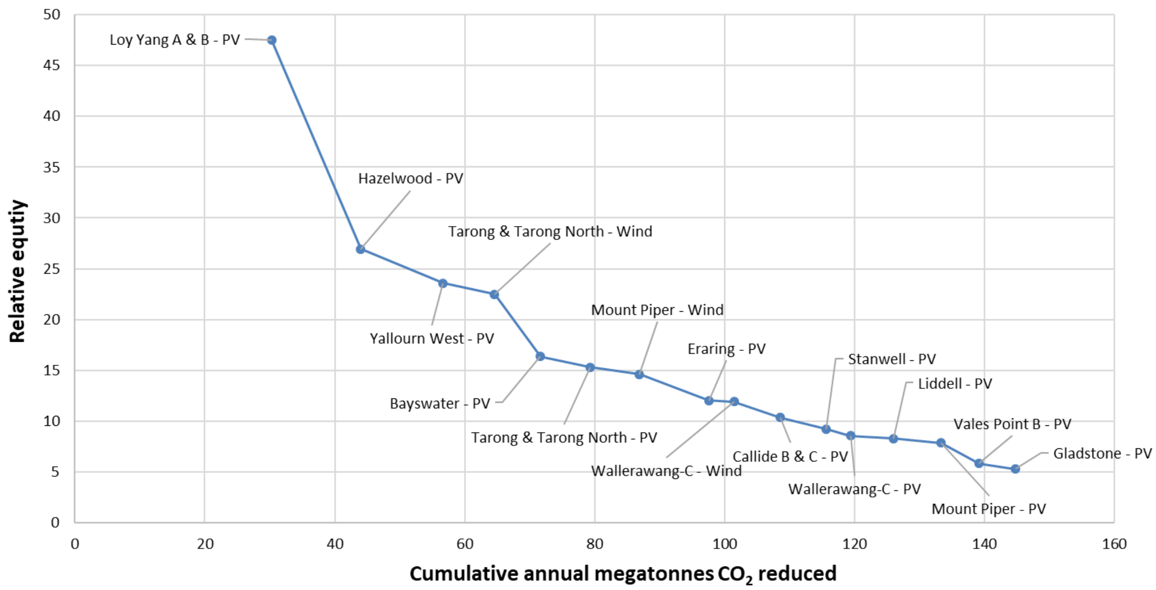

Figure 6. Mitigation equity curve for prioritising coal plant retirement in Australia

There are, of course, limitations to this assessment method – some inherent to the methodology and others to the data utilised in this specific example. The number of indicators used here as proxies for the categories considered to be vital for such an equity assessment could be expanded (for example, a more comprehensive set of health impacts) and with greater specificity of data available (for example, with household geographical location and individual income and expenditure figures), a more accurate evaluation of costs and benefits to specific households could be undertaken. But despite this, it is expected that the evaluation has some merit in allowing a relatively rapid but somewhat locally specific assessment of equity impacts. The use of a high level of localization of data is also considered to be quite novel, as many assessments apply only general technology factors for such appraisals.

There are also arguments that PV and wind plants would provide only intermittent generation, so that the comparison here is not equivalent MWh for MWh with controllable baseload generation from coal. This is a reasonable argument, particularly if there was a consideration of nationwide total replacement of coal with RE, and there are methods to ensure greater equivalency – such as the inclusion of storage to enable controllable output. The latter condition is the subject of ongoing work, as the employment figures in particular are yet to be readily available (although it is hoped that data will be obtained from projects soon to be in operation [53)]). The inclusion of storage would likely exacerbate the cost preference for higher capacity factor plants – wind and Queensland PV – which would require less equivalent storage. On the other hand, there are flow-on impacts and benefits which are not taken specifically into account in this study. For example, some power plants are mine-gate plants which form the majority or sole user of coal from these mines. The closure of the plants in some cases will flow on to a closure of the mines, which is not accounted for here. Additionally, the retirement planning sequence will have an impact on the remaining plants – particularly on their operating capacity factor if they need to increase output to cover for transitional power deficits – which would imply that the priority should be reassessed on the removal of each plant from the system. A further consideration is that (given a sufficiently interconnected electricity grid) there is an opportunity for generation to be retired at one location and built at a different location. This would change the spread of all impacts and benefits, and may also require additional considerations, such as power connection upgrades or transmission line installation.

There are a number of power plants in this set that have recently, or will soon, be retired. In particular, Wallerawang C was permanently closed in 2015, Hazelwood power plant was permanently closed in March 2017, while Liddell power plant is slated for closure in 2022 [54)]. The shutting down of Hazelwood, and the potential shutdown of Liddell [54, 55)] have both been cause for controversy in the political sphere [56)], due to the removal of large amounts of nominally low cost coal-fired base load power from the grid leading to instability, and the loss of jobs [57)]. Wallerawang C`s closure was not met with as much national coverage, which can be speculated to be due to the timing (before recent troubles in the electricity grid which have been partially blamed on renewables) and its smaller scale. From our assessment, Wallerawang`s replacement would have been one of the mid-to-lower priorities on an equity scale (**Figure 6**), but with regards to the cost of mitigation it is one of the lowest cost sites due to its ability to accommodate wind power (**Figure 4**). On the other hand, the shutting down of Hazelwood, if it was replaced with PV, would be one of the more preferable options both with regards to equity and cost. Furthermore, Liddell, from our assessment, would be neither a cost nor an equity priority for shutdown, as its replacement with PV would be costly and produce relatively lower equity benefits. However, it should be noted that the transition would still provide an increase in overall employment and reduce health impacts significantly (Table 4). With sufficient time to plan for the transition, such replacement projects could still be possible. On the practical side, Hazelwood and Liddell are both very old power stations requiring significant upgrades to be economically viable and safe, which are the main reasons they were slated for shutdown in the first place. Such practical priorities are likely to be taken into greater account by the companies that own these plants. Furthermore, ownership of the various power plants is not controlled by a single (government or non-government) entity, hence this list of priority is more of a strategic, policy-informing nature than a directly-actionable output.

It is apparent that there is a need to look at post-closure options for retirement of power plants [58)] and at the same time there is a need for replacement power that offers positive and more equitable contributions to the local community. It is also clear that some cases offer win-win solutions for both

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cost of abatement and the equity improvement produced, whereas others are either mixed or both less attractive. Such an assessment process should be considered in order to examine a variety of alternative projects that might be undertaken in order to get the most socially, economically and environmentally positive outcomes.

4. Conclusions

While existing methods for prioritizing mitigation efforts tend to rely on mitigation cost curves, it has been indicated, through the feedback elicited in the survey and a critical review of literature, that there is a need for greater recognition of social equity impacts arising from energy policy implementation and to consider non-cost impacts and benefits that may change the ranking of preferred mitigation options. Importantly, most assessments neglect the consideration of equitable distribution of benefits and impacts, particularly in a quantitative sense. In the current study, we considered the prioritization of mitigation options based on the retirement of coal-fired power plants in Australia, and the replacement of the plant with equivalent renewable energy. Mitigation curves based on cost and equity were developed, indicating different priority options.

In the analysis, a number of points were considered to be important. Reducing electricity prices benefits low income families the most and therefore has a large impact on policy burden levels, shifting the burden towards higher socio-economic groups (or rather, proportionally benefiting lower socio-economic groups due to their higher proportional expenditure on energy as a component of total expenditure). The scale of the power plant has a large impact on relative equity levels, as larger plants typically account for larger amounts of GHG and PM being reduced by their retirement. While the impact of GHG is considered to be equally shared, PM is almost always impacting on lower income families, due to the location of power plants in lower income areas. The equity factor of employment has the lowest impact on the overall equity score, as the change is not extreme (i.e. the jobs lost by fossil fuel retirement are replaced and marginally increased with RE jobs), however, there is a shift in employment types that implies greater equity. Replacement of coal plants with solar PV plant provides a larger number of jobs that benefit lower income households when compared to wind.

With the standard cost-curve approach, the wind power options were evidently preferable over the PV options, by a significant margin – however, wind power was only feasible at three of the sites. While the equity scores provided here are comparative between sites, the best performing option was the Loy Yang A & B complex – heavily influenced by its scale. However, when considering cost of mitigation as well as relative equity performance, the Tarong & Tarong North complex replacement with wind power was judged to be the most effective option. The disparity between these results is directly due to the incorporation of quantified social equity as an important factor in energy policy decision making. Through the incorporation of social considerations and of energy justice ideals, energy policy decision making can be influenced to engender not only a more efficient, but also a fairer energy system transition toward renewable energy alternatives.

This research adds to the broader body of work on energy justice evaluation through a framework for the quantification of social equity outcomes of the transition away from fossil fuel toward RE. This quantification is expressed in terms of both the improvement of social equity or 'fairness' of policy decisions and also in terms of the distribution of costs and benefits, incorporating spatial and social aspects of energy justice [59)].

Building on the expression of social equity outcomes in quantitative terms, fungible with economic and environmental outcomes, this study allows for the holistic evaluation of energy policy sustainability outcomes. This quantification, which is often (rightly or wrongly) preferred by decision-makers [60)], may better-enable the integration of energy justice concerns into the policy making process [18)] to allow for the development of evidence-based policy which can demonstrably improve energy justice outcomes for disadvantaged stakeholders.

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REFERENCES

1) UN *Transforming our world: the 2030 agenda for sustainable development*; United Nations: New York, 2015.
2) UN *Adoption of the Paris Agreement*; United Nations: Paris, 2015.
3) Lutsey, N.; Sperling, D., Greenhouse gas mitigation supply curve for the United States for transport versus other sectors. *Transportation Research Part D: Transport and Environment* **2009,** *14* (3), 222-229.
4) He, K.; Lei, Y.; Pan, X.; Zhang, Y.; Zhang, Q.; Chen, D., Co-benefits from energy policies in China. *Energy* **2010,** *35* (11), 4265-4272.
5) Puppim de Oliveira, J. A.; Doll, C. N. H.; Kurniawan, T. A.; Geng, Y.; Kapshe, M.; Huisingh, D., Promoting win–win situations in climate change mitigation, local environmental quality and development in Asian cities through co-benefits. *Journal of Cleaner Production* **2013,** *58* (0), 1-6.
6) Wagner, F.; Amann, M.; Borken-Kleefeld, J.; Cofala, J.; Höglund-Isaksson, L.; Purohit, P.; Rafaj, P.; Schöpp, W.; Winiwarter, W., Sectoral marginal abatement cost curves: implications for mitigation pledges and air pollution co-benefits for Annex I countries. *Sustainability Science* **2012,** *7* (2), 169-184.
7) Chapman, A. J.; McLellan, B.; Tezuka, T., Proposing an evaluation framework for energy policy making incorporating equity: Applications in Australia. *Energy Research & Social Science* **2016,** *21*, 54-69.
8) Chapman, A.; McLellan, B.; Tezuka, T., Strengthening the Energy Policy Making Process and Sustainability Outcomes in the OECD through Policy Design. *Administrative Sciences* **2016,** *6* (3), 9.
9) AER *State of the energy market 2014*; Australian Energy Regulator: Melbourne, Victoria, December, 2014.
10) Wang, L.; Wei, Y.-M.; Brown, M. A., Global transition to low-carbon electricity: A bibliometric analysis. *Applied Energy* **2017,** *205* (Supplement C), 57-68.
11) Fakhry, R., How clean energy and efficiency can replace coal for a reliable, modern electricity grid. *The Electricity Journal* **2017,** *30* (6), 31-41.
12) Sun, X.; Zhang, B.; Tang, X.; McLellan, B. C.; Höök, M., Sustainable energy transitions in China: Renewable options and impacts on the electricity system. *Energies* **2016,** *9* (12).
13) Merzic, A.; Music, M.; Haznadar, Z., Conceptualizing sustainable development of conventional power systems in developing countries – A contribution towards low carbon future. *Energy* **2017,** *126* (Supplement C), 112-123.
14) Geng, Z.; Conejo, A. J.; Chen, Q.; Xia, Q.; Kang, C., Electricity production scheduling under uncertainty: Max social welfare vs. min emission vs. max renewable production. *Applied Energy* **2017,** *193* (Supplement C), 540-549.
15) Sadeghi, H.; Abdollahi, A.; Rashidinejad, M., Evaluating the impact of FIT financial burden on social welfare in renewable expansion planning. *Renewable Energy* **2015,** *75* (0), 199-209.
16) Behrens, P.; Rodrigues, J. F. D.; Brás, T.; Silva, C., Environmental, economic, and social impacts of feed-in tariffs: A Portuguese perspective 2000–2010. *Applied Energy* **2016,** *173* (Supplement C), 309-319.
17) Shih, Y.-H.; Tseng, C.-H., Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach. *Applied Energy* **2014,** *119* (0), 57-66.
18) Heffron, R. J.; McCauley, D., The concept of energy justice across the disciplines. *Energy Policy* **2017,** *105*, 658-667.

19) Jenkins, K.; McCauley, D.; Heffron, R.; Stephan, H.; Rehner, R., Energy justice: A conceptual review. *Energy Research & Social Science* **2016,** *11*, 174-182.
20) McCauley, D. A.; Heffron, R. J.; Stephan, H.; Jenkins, K., Advancing energy justice: the triumvirate of tenets. *International Energy Law Review* **2013,** *32* (3), 107-110.
21) Sovacool, B. K.; Dworkin, M. H., Energy justice: Conceptual insights and practical applications. *Applied Energy* **2015,** *142*, 435-444.
22) Neuhoff, K.; Bach, S.; Diekmann, J.; Beznoska, M.; El-Laboudy, T., Distributional effects of energy transition: impacts of renewable electricity support in Germany. *Economics of Energy & Environmental Policy* **2013,** *2* (1).
23) Schlör, H.; Fischer, W.; Hake, J.-F., Measuring social welfare, energy and inequality in Germany. *Applied Energy* **2012,** *97* (Supplement C), 135-142.
24) Schlör, H.; Fischer, W.; Hake, J.-F., Sustainable development, justice and the Atkinson index: Measuring the distributional effects of the German energy transition. *Applied Energy* **2013,** *112* (Supplement C), 1493-1499.
25) Finley-Brook, M.; Holloman, E., Empowering Energy Justice. *International Journal of Environmental Research and Public Health* **2016,** *13* (9), 926.
26) Healy, N.; Barry, J., Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition". *Energy Policy* **2017,** *108* (Supplement C), 451-459.
27) Jenkins, K.; McCauley, D.; Warren, C. R., Attributing responsibility for energy justice: A case study of the Hinkley Point Nuclear Complex. *Energy Policy* **2017,** *108* (Supplement C), 836-843.
28) Geels, F. W.; Schot, J., Typology of sociotechnical transition pathways. *Research Policy* **2007,** *36* (3), 399-417.
29) Morris, C.; Jungjohann, A., Energizing the people. NATURE PUBLISHING GROUP MACMILLAN BUILDING, 4 CRINAN ST, LONDON N1 9XW, ENGLAND: 2017.
30) AEMO Australian Energy Market Operator - Facility Data Webpage. http://www.aemo.com.au/ (accessed 21 September).
31) Renewables SA Predicted wind speed at 80 metres above ground level, 1995-2005, Australia. www.renewablessa.sa.gov.au/files/121219-windresourcemappingaustralia.pdf (accessed 29 July).
32) AGL Fact Sheet: Nyngan Solar Plant. https://www.agl.com.au/-/media/AGL/About-AGL/Documents/How-We-Source-Energy/Solar-Community/Nyngan-Solar-Plant/Factsheets/2014/Nyngan-Fact-Sheet-v7.pdf?la=en (accessed 29 July).
33) AGL Fact Sheet: Broken Hill Solar Plant. www.agl.com.au/-/media/AGL/About-AGL/Documents/How-We-Source-Energy/Solar-Community/Broken-Hill-Solar-Plant/Factsheets/2014/Broken-Hill-Fact-Sheet-v8.pdf?la=en (accessed 29 July).
34) AGL Fact Sheet: Hallett Wind Farm. www.agl.com.au/about-agl/how-we-source-energy/renewable-energy/hallett-wind-farm (accessed 29 July).
35) AGL Fact Sheet: Oaklands Wind Farm. www.agl.com.au/about-agl/how-we-source-energy/renewable-energy/oaklands-hill-wind-farm (accessed 29 July).
36) AEMO Carbon Dioxide Equivalent Intensity Index (CDEII). www.http://www.aemo.com.au/-/media/Files/PDF/Carbon-Dioxide-Equivalent-Intensity-Index-Procedure-v300-FINAL-Signed.ashx (accessed 29 July).
37) Fthenakis, V. M.; Kim, H. C., Photovoltaics: Life-cycle analyses. *Solar Energy* **2011,** *85* (8), 1609-1628.
38) Guezuraga, B.; Zauner, R.; Pölz, W., Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy* **2012,** *37* (1), 37-44.
39) Council, C. E. Consumer guide to buying household solar panels (photovoltaic panels), Volume 14: 26 August 2011. https://www.hume.vic.gov.au/files/67564487-bab6-

Please reference the final published version of this paper, available from: https://doi.org/10.1016/j.apenergy.2018.03.054

4d1c-b091-a2bb011ef11a/Clean_Energy_Council_Solar_PV_Consumer_Guide.pdf (accessed 29 July).
40) Observatory, G. E., Current List of Coal Power Plants. 2016.
41) Generation, M. *Macquarie Generation Annual Report 2007*; Sydney, October 2007, 2007; p 98.
42) Energy, O. *Origin Energy Annual Report 2015*; Sydney, 18 September 2015, 2015; p 138.
43) Payscale Fossil Fuel Energy Industry Median Wages. http://www.payscale.com/research/AU/Country=Australia/Salary (accessed August 4).
44) Chapman, A. J.; McLellan, B.; Tezuka, T., Residential solar PV policy: An analysis of impacts, successes and failures in the Australian case. *Renewable Energy* **2016,** *86*, 1265-1279.
45) Payscale Average Salary for Industry: Renewable Power Generation – Australia. http://www.payscale.com/research/AU/Country=Australia/Salary (accessed August 4).
46) Brinsmead, T. S.; Hayward, J.; Graham, P.; Brinsmead, T.; Hayward, J.; Graham, P., Australian electricity market analysis report to 2020 and 2030. CSIRO Report No. EP141067: 2014.
47) Organization, W. H., Health effects of particulate matter. Policy implications for countries in eastern Europe, Caucasus and central Asia. *World Health Organization Regional Office for Europe, Copenhagen* **2013**.
48) McLellan, B. C.; Diniz Da Costa, J. C.; Dicks, A. L., Location-specific sustainability metrics: Measuring sustainability space. *Sansai* **2012,** *6*, 18.
49) NPI *Emissions Estimation Technique Manual for Fossil Fuel Electric Power Generation*; National Pollutant Inventory, : Canberra, January, 2012.
50) ABS *Census of Population and Housing: Socio-Economic Indexes for Areas (SEIFA), Australia*; Australian Bureau of Statistics: Canberra, 29/05/2008, 2006.
51) ABS *Statistics: 6032.0 – Average Weekly Earnings, Australia*; Australian Bureau of Statistics: Canberra, November 2014, 2014.
52) NPI National Pollutant Inventory Emissions Data 2010-2016. www.npi.gov.au (accessed September 21).
53) Koziol, M. South Australia announces Tesla as backer of world's largest battery. http://www.smh.com.au/federal-politics/political-news/south-australia-to-announce-tesla-as-backer-of-worlds-largest-battery-20170707-gx6mhy.html (accessed July 31st).
54) Wordsworth, M.; Yaxley, L., Liddell power station: AGL appears committed to closing coal plant despite meeting with PM. *ABC News Online* September 11, 2017, 2017.
55) Jotzo, F.; Antjum, Z., The true cost of keeping the Liddell power plant open. *The Conversation* 11 September, 2017, 2017.
56) Grattan, M., King Coal is wearing big boots in the Turnbull government. *The Conversation* 14 September, 2017, 2017.
57) Anderson, S., Hazelwood power station closure: What does it mean for electricity bills, the environment and the Latrobe Valley? *ABC News Online* March 30, 2017, 2017.
58) Lazaro, K., Hazelwood closure: Latrobe Valley 'needs jobs, not new pools' to help transition from coal industry. *ABC News Online* 2017.
59) Heffron, R. J.; McCauley, D.; Sovacool, B. K., Resolving society's energy trilemma through the Energy Justice Metric. *Energy Policy* **2015,** *87*, 168-176.
60) Corder, G. D.; McLellan, B. C.; Green, S. R., Delivering solutions for resource conservation and recycling into project management systems through SUSOP®. *Minerals Engineering* **2012,** *29* (0), 47-57.

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Appendices

Appendix A. Fossil Fuel Generation Jobs, Distribution and Remuneration

Type of Job	% of Jobs	Median Wage
Executive & senior management	5.9%	$248,942
Engineering officers	13.4%	$82,850
Professional officers	6.4%	$56,098
Administration officers	12.8%	$46,622
Operators	20%	$92,500
Mobile coal plant operators	1.5%	$62,641
Tradespersons (electrical)	4.9%	$75,505
Tradespersons (mechanical)	11.3%	$67,492
Tradespersons (metal fabrication)	1.5%	$70,039
Power workers	14.9%	$97,800
Apprentices (electrical & mechanical)	6.7%	$25,012

Note: Executive and senior management roles include cash bonuses

Appendix B. Solar PV and Wind Farm Maintenance Jobs and Remuneration.

Type of Job	Median Wage
Solar Farm Maintenance	$51,369 ($34,166~$72,264)
Wind Farm Maintenance	$70,546 ($43,626~$104,543)

Appendix C. LGA, Population and SEIFA Decile of Coal-Fired Generation Affected Households

Complex Name	Affected LGAs	LGA Population	SEIFA Decile
Bayswater	Muswellbrook	15234	5
Callide B &C	Banana	13358	7
Eraring	Newcastle	141753	6
	Lake Macquarie	183140	7
	Gosford	158157	8
Gladstone	Gladstone	29084	8
Hazelwood	Latrobe	69329	4
Liddell	Muswellbrook	15234	5
Loy Yang A & B	Latrobe	69329	4
Mount Piper	Lithgow	19759	3
Stanwell	Rockhampton	58747	5
Tarong & Tarong North	Nanango	9014	2
Vales Point B	Wyong	139801	5
	Lake Macquarie	183140	7
	Gosford	158157	8
Wallerawang-C	Lithgow	19759	3
Yallourn West	Latrobe	69329	4

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Appendix D. Income Levels, Household Income and SEIFA Deciles (in $AUS)

Income Level	Very Low		Low		Average			High		Very High
Household Income	$0~399 /week		$400~999 /week		$1000~1999 /week			$2000~3499 /week		$3500~5000 + /week
Decile	1	2	3	4	5	6	7	8	9	10

Appendix E. Higher Heating Values (HHV) for Coal Combustion (MJ converted to MWh)

State	**NSW**	**QLD**	**VIC**
HHV (MWh/tonne)	7.297	7.611	2.833